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In-situ Emission Factors for Residential Wood Combustion Units

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This report presents particulate emission factors (grams per hour, grams per kilogram) for existing traditional technology woodstoves and catalytic and noncatalytic units which meet or could meet the Environmental Protection Agency's 1988 new source performance standards.

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IN-SITU EMISSION FACTORS FOR RESIDENTIAL WOOD COMBUSTION UNITS

Emissions Standards Division

U. S. Environmental Protection Agency
Office of Air and Radiation
Office of Air Quality Planning and Standards
Research Triangle Park, North Carolina 27711

December 1988

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ABSTRACT

This document recommends particulate emission factors (grams per hour, grams per kilogram) for existing traditional technology woodstoves and catalytic and noncatalytic units which meet (certified) or could meet (certifiable) the U.S. Environmental Protection Agency's (EPA) 1988 (Phase I) New Source Performance Standards (NSPS). This information is to assist EPA regional offices and state agencies in estimating the emission contribution from existing technology woodstoves and the airshed impact of replacing those woodstoves with units that meet the NSPS.

The woodstove emission factors are based on field emission studies conducted during the 1985–86, 1986–87, and 1987–88 heating seasons in three localities in North America. The emission factors for the traditional technology woodstoves are based on how those units are presently and in future years are expected to perform. The emission factors for 1988 NSPS certified/certifiable woodstoves are based on how these units should perform in future years.

While significant emission rate variability was demonstrated in field studies, there are several cases where individual certified woodstoves and/or woodstove models (both catalytic and noncatalytic) have shown relatively low emission rates and variability. These observations indicate that it is possible for new technology woodstoves to consistently produce relatively low emissions. It is therefore expected as emission control technology improves for NSPS-certified woodstoves, that a more consistent pattern of relatively low emission rate performance will be demonstrated in future studies.

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I. INTRODUCTION

The Environmental Protection Agency (EPA) has promulgated New Source Performance Standards (NSPS) for residential woodstoves.[1] The purpose of this report is to determine appropriate particulate emission factors (gram per hour [g/hr] and gram per kilogram [g/kg]) for existing traditional technology woodstoves and those units which meet or could meet NSPS requirements for catalytic and noncatalytic stoves. This information is to assist EPA regional offices and state agencies in estimating the emission contribution from existing technology woodstoves and the airshed impact of replacing those woodstoves with units that meet the NSPS.

The NSPS includes emission limits for new woodstoves based upon testing conducted under laboratory conditions. Recent in-home studies[2,3,4,5,6,7] of woodstove particulate emission performance have produced data which suggest that woodstoves perform differently under actual in-the-home operating conditions than under laboratory test conditions. In addition, the in-home emission rate data collected to date have demonstrated significant particulate emission rate (g/hr and g/kg) variability within woodstove technology categories (traditional and NSPS "certified/certifiable" woodstoves [catalytic and non-catalytic]), and within specific woodstove models. The term "NSPS certified/certifiable" refers to woodstoves that are (1) 1988 Oregon certified woodstoves that have been "grandfathered" under Phase I NSPS provisions and (2) 1988 Oregon certified woodstoves that could have been "grandfathered" under the NSPS[1]. There were no woodstoves used in any of the field studies that were directly certified under the EPA 1988 (Phase I) or 1990 (Phase II) New Source Performance Standards (NSPS). Therefore, the 1988 NSPS certified/certifiable woodstoves used in the field studies represent a "first generation" of woodstove emission control technology which appears to be a contributing factor to the observed *in-situ* emission rate variability. Woodstoves "grandfathered" under 1988 NSPS provisions are not subject to the more stringent direct-certification requirements of the NSPS.

The observed variability in measured "real world" emission rates for woodstoves has been attributed to the following factors:

- Differences in fueling patterns (e.g., frequency, fuel load density) between woodstove operators;
- Differences in woodstove installations and chimney systems;
- Differences in burn rates between woodstoves;
- Differences in fuel characteristics in each home, or by region;
- Differences in how by-pass damper(s) and/or air draft settings are used; and

- Differences in the integrity of key components of the emission control system of each woodstove over time, e.g., catalysts, by-pass damper gaskets, fueling or ash clean-out door seals, etc.

While significant emission rate variability has been demonstrated, there are several cases where individual certified woodstoves and/or woodstove models (both catalytic and noncatalytic) have shown relatively low emission rates and variability. These observations indicate that it is possible for new technology woodstoves to consistently produce relatively low emissions. It is therefore expected as emission control technology improves for NSPS direct-certified woodstoves, that a more consistent pattern of relatively low emission rate performance will be demonstrated in future studies.

II. CONCLUSIONS & RECOMMENDATIONS

The recommended particulate emission factors (g/hr, g/kg) are based on *in-situ* emission studies conducted during the 1985–86, 1986–87, and 1987–88 heating seasons[2,3,4,5,6,7]. Emission factors have been developed for the following three catagories of woodstoves:

- Traditional Technology (pre-NSPS) woodstoves;
- 1988 NSPS Certified/Certifiable Catalytic woodstoves; and
- 1988 NSPS Certified/Certifiable Noncatalytic woodstoves.

The term "NSPS Certified/Certifiable" refers to woodstoves that are: (1) 1988 Oregon Certified woodstoves that have been "grandfathered" under Phase I NSPS provisions, and (2) 1988 Oregon Certified woodstoves that could have been "grandfathered" under the NSPS[1]. Since there were no 1988 or 1990 NSPS direct-certified woodstoves in any of the *in-situ* studies, there are no recommended emission factors for these technology categories.

The traditional technology woodstove emission factors were based on judgements which considered differences in woodstove operation, installation, and fueling patterns in different geographic areas. The recommended emission factors for this woodstove technology category are based on how these units *presently* and should continue to perform.

The recommended particulate emission factors (g/hr, g/kg) for 1988 NSPS certified/certifiable woodstoves (catalytic and noncatalytic) are based on how these units *should* perform in future years. This approach is based on observations that: (1) several of the woodstove units demonstrating elevated emission rates could be considered "first generation" technology which is expected to improve over time, and (2) there was inferential evidence that new technology woodstoves properly installed, operated, and maintained could produce consistently low emissions.

The recommended emission factors are also based on the assumption that woodstove emission control, installation, and maintenance problems identified in field studies have been or will be addressed by the woodstove industry and/or regulatory agencies.

The recommended particulate emission factors (g/hr, g/kg) are presented in Table II-1. Also included in this table are several related statistical measures which are based on the data used to derive the emission

Table II-1

Recommended Particulate Emission Factors for Woodstoves

	Traditional Technology Woodstoves		Catalytic Woodstoves (1988 NSPS Certified/Certifiable)		Noncatalytic Woodstoves (1988 NSPS Certified/Certifiable)	
	g/hr	g/kg	g/hr	g/kg	g/hr	g/kg
Emission Rate	21.3	15.2 *	6.2	6.6	9.2	9.6
Standard Deviation	7.4	4.7	2.5	2.2	5.5	5.5
95% Confidence Interval	21.3 ± 2.8	15.2 ± 1.8	6.2 ± 2.2	6.6 ± 1.9	9.2 ± 3.8	9.6 ± 3.8
99% Confidence Interval	21.3 ± 3.7	15.2 ± 2.4	6.2 ± 2.8	6.6 ± 2.5	9.2 ± 5.0	9.6 ± 5.0

* For Traditional Technology woodstoves only, the g/kg emission factor may be calculated using the following equation:

$y = -9.77 x + 29.2,$

where

x = Area-specific average burn rate, dry kg/hr; and

y = Emission rate, g/kg.

factors. Since the data bases upon which these emission factors are based are relatively small, the user should apply the appropriate statistical caveats, e.g., confidence limits, when using the recommended emission factors on either an absolute or relative comparison basis.

The equation shown below Table II-1 can be used to calculate a gram-per-kilogram (g/kg) emission factor for traditional technology woodstoves based on the average burn rate (dry kg/hr) in a specific geographic area if burn rate information is available. At this time there are no recommendations regarding adjusting either the gram-per-hour or gram-per-kilogram emission factors for the 1988 NSPS certified/certifiable woodstoves due to the limited amount of *in-situ* emission and burn rate data available.

Since the data bases used to determine the recommended emission factors are relatively small, it is recommended that additional *in-situ* data for traditional technology and NSPS-certified woodstoves be collected to reduce the associated statistical uncertainty. Additional emission and burn rate data may provide the basis upon which area-specific emission factors for NSPS-certified woodstoves could be recommended.

III. TECHNICAL APPROACH

A. TRADITIONAL TECHNOLOGY WOODSTOVE EMISSION FACTORS

There have been four studies[2,3,4,6] conducted during the 1985–86 and 1986–87 heating seasons which evaluated the in-the-home (*in-situ*) particulate emission performance of traditional technology or pre-NSPS woodstoves. These studies were conducted in three regions of North America: Northeastern United States as represented by limited areas of upstate New York and Vermont[2], the Portland, Oregon metropolitan area[3,4], and the City of Whitehorse, Yukon Territory, Canada.[6]

All four studies including two other studies which only evaluated the *in-situ* emission performance of new technology woodstoves[5,7], used the same type of sampling equipment, the Automated Woodstove Emission Sampler (AWES). The operational and design characteristics of the AWES have been described in detail in several reports[2,3,4,6,8,9]. This emission sampler was designed specifically to measure residential wood combustion (RWC) particulate emissions under *in-situ* operating conditions. A recent study determined the upper-limit absolute difference of emission rates between AWES and EPA reference sampling Methods 5G and 5H was 2.0 g/hr[4]. However, this study concluded that when considering the sampling accuracies associated with Methods 5G, 5H, and the AWES, there were no statistically significant differences in the emission rates between the three sampling methods.

Data used to produce previous emission factors for woodstoves were based primarily on laboratory tests[10]. These tests employed a wide variety of sampling methods and fueling techniques which preceded the adoption of uniform fueling and sampling method protocols as developed by the Oregon Department of Environmental Quality[11] and the U.S. Environmental Protection Agency (EPA)[1]. It is therefore difficult to make any direct comparisons between the *in-situ* data determined by the AWES system and previous laboratory studies. Since the AWES emission rates are: (1) comparable with emission rates as determined by EPA reference woodstove particulate sampling methods; and (2) based on "real world" operating conditions, only AWES-determined particulate emission rate (g/hr and g/kg) data are considered in the determination of recommended emission factors for traditional technology and NSPS-certified/certifiable woodstoves.

Presented in Table III-1 is a list of woodstove models and *in-situ* emission samples collected per woodstove model for each region. Since hundreds of models of traditional technology woodstoves have been produced over the last several decades,[12] the issue of representativeness should be addressed initially. In reviewing the study designs for each of the completed woodstove field studies, it appears only the

Table III-1

Woodstove Models and Number of Emission Samples Collected During Field Studies (Traditional Technology Woodstoves)

Study Area	Stove Model	Emission samples
"Northeast"[2]	T-A	4
	T-B	1
	T-C	3
	T-G	3
	T-H	2
	T-I	1
		—
		14
"Northwest"[3,4]	T-B	5
	T-D	5
	T-J	1
	T-K	1
		—
		12
"Whitehorse"[6]	T-B	4
	T-E	4
	T-F	4
	T-L	4
	T-M	6
	T-N	6
	T-O	3
	T-P	10
	T-Q	20
		—
		61

Total Woodstove Models Evaluated	17
Total Emission Samples	87

"Whitehorse" study included woodstoves in direct proportion to the types of traditional technology woodstove models installed throughout the City of Whitehorse. This was a relatively easy task, since one woodstove model, T-Q, has been installed in approximately 40 percent of the homes in the Whitehorse area[13]. For larger metropolitan areas, or areas with a more diverse population of installed models, the selection of homes based on the type of woodstove models installed becomes a much more difficult task if resources only allow a limited number of homes to be included in a particular study. Since the number of woodstove models included in the "Northeast" and "Northwest" studies is limited, the emission data generated may not be representative of the full range or average of expected emission rates for these areas.

Table III-2 presents the *in-situ* emission rate data initially considered in the development of emission factors for traditional technology woodstoves. Also included in this table is information regarding the type of chimney system attached to each woodstove and average burn rate during each emission sampling period. A review of woodstove use and other information associated with each particulate emission sample led to a decision not to include eight emission samples from the Whitehorse Efficient Woodheat Demonstration Study[6] (values deleted in parentheses). Seven of the deleted emission samples exceeded the quality assurance (QA) objective that the ambient oxygen value should be within 20.9±2.0% absolute at the end-of-sampling-period calibration. Calculated emissions (g/hr, g/kg) have a potentially higher degree of associated uncertainty when this QA criteria is exceeded. One additional sample was deleted due to the level of uncertainty associated with the emission rate calculation. This calculation was based on an assumed upper-limit value of sample collected in the methanol solvent rinse. Since average emission rates reported in both the "Northeast Cooperative Woodstove Study"[2] and the "Northwest" studies[3,4] did not include individual emission samples exceeding these quality assurance objectives in the calculation of mean emission rates, the eight data sets are deleted from the mean emission rates shown in subsequent tables in this report.

Since significant intra- and inter-stove model emission rate variabilities are shown in the results from all three study areas, there appeared to be no justifiable reason to delete other data. There is no reason to believe the range of emission rates shown in Table III-2 is not to be expected for traditional technology woodstoves. This variability is demonstrated in the data in Tables III-3 and III-4. Table III-3 summarizes mean emission rates (g/hr and g/kg) and burn rates (dry kg/hr) by each home (installation) in the three study areas. Table III-4 summarizes mean emission and burn rates by woodstove model. Inter-home emission rate variability is most clearly demonstrated by the woodstove model T-Q emission rates. The range of average emission rates for woodstove model T-Q are 16.8 to 35.3 g/hr and 7.4 to 23.1 g/kg (Table III-3) with average emission rates of 23.5 g/hr and 16.7 g/kg (Table III-4). The percentage differences in gram-per-hour and gram-per-kilogram emission rates between the lowest (Home W11) and highest (Home W01) average values were 110% and

"Whitehorse" study included woodstoves in direct proportion to the types of traditional technology woodstove models installed throughout the City of Whitehorse. This was a relatively easy task, since one woodstove model, T-Q, has been installed in approximately 40 percent of the homes in the Whitehorse area[13]. For larger metropolitan areas, or areas with a more diverse population of installed models, the selection of homes based on the type of woodstove models installed becomes a much more difficult task if resources only allow a limited number of homes to be included in a particular study. Since the number of woodstove models included in the "Northeast" and "Northwest" studies is limited, the emission data generated may not be representative of the full range or average of expected emission rates for these areas.

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Table III-2

Installation, Burn and Particulate Emission Rate Characteristics
Traditional Technology Woodstoves

Stove Model	Study Area	Home Code	Chimney Type	Sample Period	Burn Rate dry kg/hr	Emissions		Ref.	Comments
						g/hr	g/kg		
T-A	"Northeast"	V06	II	1	2.45	2.9	1.2	2	a
				2	1.60	4.7	2.9		a
				5	1.52	12.7	8.4		
				6	1.86	17.3	9.3		
T-B	"Northeast"	V09	II	1	1.12	15.4	13.7	2	
	"Northwest"	P03	II	1	1.68	22.3	13.3	4	
				2	1.26	9.7	7.7		
				3	1.02	10.8	10.5		
				4	0.94	9.5	10.1		
				5	1.25	16.7	13.4		
	"Whitehorse"	W10	V	1	1.28	28.6	22.4	6	
				2	1.15	16.5	14.4		
				3	1.44	22.5	15.6		
				4	1.49	24.6	16.5		
T-C	"Northeast"	V14	IV	1	1.67	16.9	10.2	2	
				2	1.45	23.5	16.3		
				3	0.92	20.3	22.0		
T-D	"Northwest"	P05	I	1	1.37	29.4	21.4	4	b
				2	1.12	28.7	25.6		
				3	0.94	21.4	22.9		
				4	1.01	27.1	26.7		
				5	0.92	20.9	22.7		
T-E	"Whitehorse"	W03	VI	1	1.18	5.7	4.8	6	
				2	1.04	8.6	8.3		
				3	1.31	(13.3)	(10.2)		c
				4	1.44	10.1	7.0		
T-F	"Whitehorse"	W12	VI	1	1.76	26.7	15.1	6	
				2	1.44	20.3	14.1		
				3	1.49	(24.7)	(16.6)		
				4	1.82	29.4	16.2		

(continued)

Table III-2
(continued)

Stove Model	Study Area	Home Code	Chimney Type	Sample Period	Burn Rate dry kg/hr	Emissions g/hr	Emissions g/kg	Ref.	Comments
T-G	"Northeast"	N08	IV	4 5 6	1.91 2.19 2.00	32.6 26.6 30.9	17.1 12.2 15.4	2	d
T-H	"Northeast"	N14	IV	6 7	2.45 1.57	34.0 29.0	13.9 18.4	2	
T-I	"Northeast"	N16	IV	1	1.55	13.9	9.0	2	
T-J	"Northwest"	O05	V	1	1.41	23.1	16.4	3	
T-K	"Northwest"	O20	V	1	1.08	18.8	17.5	3	e
T-L	"Whitehorse"	W05	VI	1 2 3 4	1.67 1.59 1.64 1.73	10.9 14.1 13.4 18.7	6.5 8.9 8.1 10.8	6	
T-M	"Whitehorse"	W04	VI	1 2 3 4	1.90 1.25 2.01 1.87	40.7 29.2 35.7 26.3	21.4 23.3 17.8 14.1	6	f
		W13	V	2 3	1.85 1.74	33.0 26.7	17.9 15.4	6	f
T-N	"Whitehorse"	W07	VI	2 3 4	1.88 2.12 2.57	32.8 21.5 (35.0)	17.5 10.1 (13.6)	6	 c
		W09	V	1 2 3	0.93 0.70 0.88	18.2 17.7 11.3	19.5 25.4 12.8	6	
T-O	"Whitehorse"	W06	VI	1 3 4	1.22 1.26 1.13	19.2 18.8 15.7	16.5 15.3 12.0	6	

(continued)

Table III-2
(continued)

Stove Model	Study Area	Home Code	Chimney Type	Sample Period	Burn Rate dry kg/hr	Emissions g/hr	Emissions g/kg	Ref.	Comments
T-P	"Whitehorse"	W06	VI	5	1.11	(19.1)	(17.2)	6	c
				6	0.77	(20.9)	(27.4)		c
				7	1.14	16.1	14.1		
				8	0.66	12.6	18.9		
				9	0.61	10.0	16.5		
		W13	V	5	1.29	33.2	25.7	6	
				6	1.35	16.4	12.2		
				7	1.19	22.9	19.3		
				8	0.89	17.5	19.6		
				9	0.89	17.8	20.0		
T-Q	"Whitehorse"	W01	V	1	1.93	49.8	25.8	6	
				2	1.32	30.4	23.1		
				4	1.26	25.8	20.5		
		W02		1	1.45	28.9	20.0	6	
				2	1.29	17.2	13.3		
				3	1.46	17.3	11.8		
				4	0.90	(11.5)	(12.8)		g
				8	0.75	17.7	23.6		
				9	0.56	13.1	23.3		
		W08	VI	2	1.65	22.5	15.0	6	
				3	1.50	(31.3)	(24.1)		c
				4	1.30	31.7	16.7		
		W11	VI	1	2.37	10.5	4.4	6	
				2	2.02	14.1	7.0		
				3	2.02	23.6	11.7		
				4	2.60	18.9	7.2		
		W14	V	1	1.16	24.7	21.4	6	
				2	1.07	25.7	23.9		
				3	1.04	(32.6)	(31.4)		c
				4	1.71	28.0	16.4		
All Areas		Mean (edited data)			1.44	21.0	15.4		
		σ_{n-1}			0.45	8.6	5.9		

(continued)

Table III-2
(continued)

Chimney Types

Code	Description
I	Unlined masonry chimney located primarily inside the exterior walls of the house
II	Tile-lined masonry chimney located primarily inside the exterior walls of the house
III	Unlined masonry chimney located primarily outside the exterior walls of the house
IV	Tile-lined masonry chimney located primarily outside the exterior walls of the house
V	Prefabricated metal chimney located primarily inside the exterior walls of the house
VI	Prefabricated metal chimney located primarily outside the exterior walls of the house

Comments:

a. It was observed that the users of this stove maintained a deep ash bed (15 to 25 cm [6 to 9 in.]) when operating this stove. This ash bed condition effectively reduced the firebox size of the stove from 84 liters (2.95 cubic feet) to 44 liters (1.6 cubic feet) and may have been a contributing factor to this relatively low emission rate.

b. This stove model was an insert mounted into an unlined masonry chimney.

c. Ambient oxygen (O_2) value associated with emission sample greater than 20.9 ± 2.0 percent absolute at final calibration. Therefore, calculated emissions (g/hr, g/kg) have a potentially higher degree of associated uncertainty. Because of the higher uncertainty associated with this emission sample, it is deleted from the data base for calculating emission factors.

d. Operators of this stove kept firebox relatively full of fuel and the primary air inlets at a low setting. This operating practice may have contributed to the relatively high observed emission rates.

e. While stove T-K had a relatively large firebox of 148 liters (5.2 cubic feet), the operator of this stove fueled this stove with small loads, i.e. average fuel load density of 12 kg/m^3 (0.73 lb/ft^3).

f. Woodstove model T-M is a "cabinet style" convection heater with an underfire primary air combustion system. This type of combustion system tends to produce elevated emissions in wood-fired stoves.

g. Estimated upper-limit emission rate due to loss of methanol solvent rinse. These emission rates were eliminated from the data base to calculate emission factors due to the associated uncertainty.

Table III-3

Mean Particulate Emission and Burn Rates by Woodstove Installation
Traditional Technology Woodstoves

Study Area	Model	Home	Mean Emission Rates		Mean Burn Rate dry kg/hr (σ_{n-1})	Emission Samples (N)
			g/hr (σ_{n-1})	g/kg (σ_{n-1})		
"Northeast"	T-A	V06	9.4 (5.9)	5.5 (3.5)	1.80 (0.34)	4
	T-B	V09	15.4 (0)	13.7 (0)	1.12 (0)	1
	T-C	V14	20.2 (2.7)	16.2 (4.8)	1.35 (0.31)	3
	T-G	N08	30.0 (2.5)	14.9 (2.0)	2.01 (0.11)	3
	T-H	N14	31.5 (2.5)	16.2 (2.3)	2.06 (0.37)	2
	T-I	N16	13.9 (0)	9.0 (0)	1.55 (0)	1
Avg (unweighted)			20.1 (8.9)	12.6 (4.4)	1.65 (0.37)	
Range			9.4 - 30.0	5.5 - 16.2	1.12 - 2.06	14
"Northwest"	T-B	P03	13.8 (5.6)	11.0 (2.4)	1.23 (0.29)	5
	T-D	P05	25.5 (4.1)	23.9 (2.2)	1.07 (0.18)	5
	T-J	O05	23.1 (0)	16.4 (0)	1.41 (0)	1
	T-K	O20	18.8 (0)	17.5 (0)	1.08 (0)	1
Avg (unweighted)			20.3 (5.1)	17.2 (5.3)	1.19 (0.16)	
Range			13.8 - 25.5	11.0 - 23.9	1.07 - 1.41	12
"Whitehorse"	T-B	W10	23.1 (5.0)	17.2 (3.6)	1.34 (0.16)	4
	T-E	W03	8.1 (2.2)	7.6 (2.3)	1.24 (0.17)	3
	T-F	W12	25.5 (4.7)	15.1 (1.05)	1.67 (0.20)	3
	T-L	W05	14.3 (5.0)	8.6 (1.8)	1.66 (0.06)	4
	T-M	W04	33.0 (6.5)	19.2 (4.1)	1.76 (0.34)	4
	T-M	W13	29.9 (4.5)	16.6 (1.8)	1.80 (0.08)	2
	T-N	W07	27.2 (8.0)	13.8 (5.2)	2.00 (0.17)	2
	T-N	W09	15.7 (3.8)	19.2 (6.3)	0.99 (0.33)	3
	T-O	W06	17.9 (1.9)	14.6 (2.3)	1.19 (0.11)	3
	T-P	W06	12.9 (3.1)	16.5 (2.4)	0.80 (0.29)	3
	T-P	W13	21.6 (7.0)	19.4 (4.8)	1.12 (0.22)	5
	T-Q	W01	35.5 (12.7)	23.1 (2.6)	1.50 (0.37)	3
	T-Q	W02	18.8 (5.9)	18.4 (5.5)	1.10 (0.41)	5
	T-Q	W08	27.1 (6.5)	15.8 (1.2)	1.46 (0.25)	2
	T-Q	W11	16.8 (5.7)	7.4 (2.7)	2.25 (0.28)	4
	T-Q	W14	26.1 (1.7)	20.5 (3.8)	1.31 (0.35)	3
Avg (unweighted)			22.1 (7.6)	15.8 (4.6)	1.45 (0.39)	
Range			8.1 - 33.0	7.4 - 23.1	0.80 - 2.25	53
ALL AREAS Avg (unweighted)			21.3 (7.4)	15.2 (4.7)	1.46 (0.37)	
Range			8.1 - 33.0	5.5 - 23.9	0.80 - 2.25	79

Table III-4

Mean Particulate Emission and Burn Rates by Woodstove Model
Traditional Technology Woodstoves

Stove Model	Study Area(s)	Homes(s)	Mean Emission Rates		Mean Burn Rate dry kg/hr (σ_{n-1})	Emission Samples (N)
			g/hr (σ_{n-1})	g/kg (σ_{n-1})		
T-A	NE	V06	9.4 (5.9)	5.5 (3.5)	1.80 (0.34)	4
T-B	NE,NW,WH	V09, P03, W10	17.6 (6.6)	13.8 (4.0)	1.26 (0.22)	10
T-C	NE	V14	20.2 (2.7)	16.2 (4.8)	1.35 (0.31)	3
T-D	NW	P05	25.5 (4.1)	23.9 (2.2)	1.07 (0.18)	5
T-E	WH	W03	8.1 (2.2)	7.6 (2.3)	1.24 (0.17)	3
T-F	WH	W12	25.5 (4.7)	15.1 (1.05)	1.67 (0.20)	3
T-G	NE	N08	30.0 (2.5)	14.9 (2.0)	2.01 (0.11)	3
T-H	NE	N14	31.5 (2.5)	16.2 (2.3)	2.06 (0.37)	2
T-I	NE	N16	13.9 (0)	9.0 (0)	1.55 (0)	1
T-J	NW	O05	23.1 (0)	16.4 (0)	1.41 (0)	1
T-K	NW	O20	18.8 (0)	17.5 (0)	1.08 (0)	1
T-L	WH	W05	14.3 (5.0)	8.6 (1.8)	1.66 (0.06)	4
T-M	WH	W04, W13	31.9 (5.6)	18.3 (3.9)	1.77 (0.27)	6
T-N	WH	W07, W09	18.3 (9.6)	17.1 (5.9)	1.30 (0.65)	5
T-O	WH	W06	17.9 (1.9)	14.6 (2.3)	1.19 (0.11)	3
T-P	WH	W06, W13	18.3 (7.1)	18.3 (4.1)	1.00 (0.28)	8
T-Q	WH	W01, W02, W08 W11, W14	23.5 (9.2)	16.7 (6.6)	1.52 (0.54)	17
Average (unweighted)			20.4 (7.0)	14.6 (4.6)	1.47 (0.32)	79
Range			8.1 - 31.9	7.6 - 23.9	0.83 - 2.06	

212%, respectively. Since woodstove model T-Q emission rates are based on measurements from five homes (17 samples), woodstove model-specific average emission rates based on limited observations, i.e. one home, probably have a high degree of uncertainty. Emission rate variability is also demonstrated by woodstove models T-B, T-N, and T-P. The ranges of average gram-per-hour emission rates for woodstove models T-B, T-N, and T-P are 13.8 to 23.1 g/hr, 15.7 to 27.2 g/hr, and 12.9 to 21.6 g/hr, respectively (refer to Table III-3).

From a statistical viewpoint, the sample sizes of the "Northeast" and "Northwest" studies appear to be too small to adequately quantify the mean emission rates for traditional technology woodstoves in these areas. As a practical upper limit, the limit (L) around the sample mean should not be greater than 3.0 units at the 99 percent confidence limit for gram-per-hour emission rate data. This value of "L" was selected because of the estimated 2.0 g/hr absolute upper-limit accuracy of the AWES[4]. The 95 percent and 99 percent confidence limits can be expressed by the following equations:

$$L = 1.96\,\sigma / N^{1/2} \quad \text{(95\% Confidence Limit)} \qquad \text{(Equation 1)}$$

$$L = 2.57\,\sigma / N^{1/2} \quad \text{(99\% Confidence Limit)} \qquad \text{(Equation 2)}$$

where: σ = assumed population standard deviation; and

N = sample size.

The minimum number of samples (N) needed can be determined by assuming a representative standard deviation (σ) of 8.6 for gram per hour emission rate data (based on data in Table III-2). Solving equations 1 and 2 for N (L=3.0), N is calculated to be 32 (95 percent confidence limit) and 54 (99 percent confidence limit). Assuming the emission samples are randomly distributed, the calculated N value implies that only the "Whitehorse" data base is sufficiently large to characterize the area-specific mean emission rate for traditional technology woodstoves within the desired confidence limit. Therefore, no recommendations regarding region-specific emission rates are made because the "Northeast" (N=14) and "Northwest" (N=12) emission rate data bases are smaller than the minimum. The recommended emission rates (g/hr, g/kg) are therefore based on an analysis of the emission rate data from all *in-situ* woodstove emission study areas.

B. 1988 NSPS-CERTIFIED/CERTIFIABLE WOODSTOVE EMISSION FACTORS

Four studies[2,4,5,7] conducted during the 1985-86, 1986-87, and 1987-88 heating seasons evaluated the *in-situ* emission performance of 1988 NSPS certified or certifiable woodstoves (catalytic and noncatalytic). The term "certified" applies to woodstove models which have been approved under 1988 emission standards of the Oregon Department of Environmental Quality (ODEQ)[11] and have been "grandfathered" under provisions of the NSPS[1]. The term "certifiable" applies to "1988 Oregon" approved woodstove models used in the *in-situ* studies which could have been "grandfathered." Oregon certification requirements for woodstoves are less rigorous than those for EPA NSPS direct-certified woodstoves. For example, data selectivity is not permitted

under the direct certification provisions of the NSPS, whereas it is allowed under the Oregon certification rules. Neither 1988 nor 1990 direct-certified NSPS certified woodstoves (either catalytic or noncatalytic) were included in any of the woodstove field studies, and therefore recommended emission factors are not developed for these woodstove categories. Table III-5 lists the catalytic and noncatalytic woodstove models that were evaluated in field studies and were either certified or certifiable under the 1988 NSPS emission limits. Also listed is the number of particulate emission samples collected per woodstove model.

Field tests of various models of 1988 NSPS certified/certifiable woodstoves demonstrated significant emission rate variability both between homes with the same woodstove model and between different woodstove models. Field tests of several models of woodstoves conducted during the 1985 through 1988 heating seasons have shown that *in-situ* emission rates of NSPS-certified woodstoves are generally higher (in the range of 1 to 20 times higher) than laboratory certification levels.

The recommended particulate emission factors (g/hr, g/kg) for 1988 NSPS certified/certifiable woodstoves (catalytic and noncatalytic) are based on how these units *should perform* in future years. This approach to evaluating emission data is based on observations that: (1) several of the woodstove units demonstrating elevated emission rates could be considered "first generation" technology, and (2) there was inferential evidence that new technology woodstoves properly installed, operated, and maintained could consistently produce low emissions. Therefore, the following criteria were used in determining whether or not individual emission samples should be included in the data bases to determine emission factors for catalytic and non-catalytic woodstoves:

1. Emission rate data which does not meet quality assurance objectives is deleted.
2. Emission rate data which are representative of a specific combination of catalytic woodstove model and a catalytic combustor which is no longer available to the consumer as of July 1, 1988 are deleted.
3. Emission rate data which appear to be anomalous, e.g., outlier, and appear to have resulted from poor operator practices that are correctable through an improved public education program are deleted. It is assumed that the woodstove industry, e.g. manufacturers, retailers, chimney sweeps/installers, etc., and/or regulatory agencies will develop and provide improved public education programs to address proper woodstove installation, maintenance, and operating practices.
4. Emission rate data which appears to be anomalous and to have been influenced by an incompatible chimney system installation is deleted. (Note: There is presently only inferential evidence that

Table III-5

Woodstove Models and Number of Emission Samples Collected During Field Studies (1988 NSPS Catalytic and Noncatalytic Certified or Certifiable Woodstoves)

Study Area	Technology	Stove Model	Samples	NSPS Status
"Northeast"[2]	Catalytic	C-A	15	Certified
		C-D	1	Certified
	Noncatalytic	NC-A	4	Certified
		NC-B	7	Certified
"Northwest"[4,5]	Catalytic	C-A	5	Certified
		C-B	3	Certified
	Noncatalytic	NC-B	5	Certified
		NC-C	4	Certifiable
"Whitehorse"[6]	Catalytic	C-A	9	Certified
		C-C	10	Certifiable
	Noncatalytic	NC-D	10	Certified

Total Woodstove Models Evaluated	Catalytic	4
	Noncatalytic	4
Total Emission Samples	Catalytic	43
	Noncatalytic	30

"oversized" or "undersized" chimney systems may influence NSPS-certified woodstoves emission performance. Additional research is needed to confirm if there is a "cause and effect" relationship between emission rates and chimney system configuration as installed with NSPS-certified woodstoves. If future studies confirm that improperly designed chimney systems adversely affect the emission performance of NSPS-certified woodstoves, regulatory agencies may modify certification programs to address this issue.)

In selecting this criteria, it is assumed that woodstove emission control, installation, and maintenance problems identified in field studies have been or will be addressed by the woodstove industry and/or regulatory agencies.

The above criteria are used to delete all values in parentheses, ( ), in Tables III-6 and III-7 from the data bases used to determine emission factors for 1988 NSPS-certified/certifiable woodstoves. Tables III-8 and III-9 show mean emission rates (g/hr and g/kg) and burn rates (dry kg/hr) for each installation and for each woodstove model for catalytic technology woodstoves (1988 NSPS certified/certifiable). Tables III-10 and III-11 show mean emission and burn rates (by installation and by woodstove model) for noncatalytic woodstoves (1988 NSPS certified/certifiable).

Table III-6

Installation, Burn and Particulate Emission Rate Characteristics
Catalytic Woodstoves (1988 NSPS Certified/Certifiable)

Stove Model	Study Area	Home Code	Chimney Type	Catalytic Combustor Model	Sample Period	Burn Rate dry kg/hr	Emissions g/hr	Emissions g/kg	Ref.	Comments
C-A	"Northeast"	V05	IV	A	4	0.84	(9.0)	(10.8)	2	a
					5	0.92	(31.4)	(34.1)		a
		V11	II	A	2	1.02	(6.1)	(6.0)	2	a,b
					6	1.19	(6.3)	(5.3)		a,b
					7	1.15	(7.0)	(6.1)		a,b
		N09	IV	A	1	1.23	(15.7)	(12.8)	2	a
					4	1.31	(21.2)	(16.2)		a
					6	1.23	(17.1)	(13.9)		a
					7	1.37	(29.6)	(21.5)		a
		N18	IV	A	4	1.37	(20.6)	(15.1)	2	a
					5	1.57	(41.3)	(26.4)		a
					6	1.19	(31.6)	(26.5)		a
					7	1.40	(29.2)	(20.8)		a
		C01	IV	B	1	0.89	4.7	5.3	7	
					2	0.84	5.1	6.1		
	"Northwest"	P02	V	B	1	1.07	2.7	2.5	4	
					2	0.95	4.2	4.4		
					3	0.87	4.7	5.4		
					4	0.79	4.3	5.4		
					5	0.70	4.3	6.3	5	f
	"Whitehorse"	W07	VI	A	5	1.72	(7.4)	(4.3)	6	a
					6	1.62	(7.5)	(4.6)		a
					8	1.85	(21.0)	(11.4)		a
					9	1.48	(25.4)	(17.2)		a,c
		W11	VI	A	5	1.84	(13.1)	(7.1)	6	a
					6	1.91	(22.0)	(11.5)		a
					7	1.64	(11.3)	(6.9)		a
					8	1.48	(12.0)	(8.1)		a
					9	1.69	(19.4)	(11.5)		a,c,d

(continued)

Table III-6
(continued)

Stove Model	Study Area	Home Code	Chimney Type	Catalytic Combustor Model	Sample Period	Burn Rate dry kg/hr	Emissions g/hr	Emissions g/kg	Ref.	Comments
C-B	"Northwest"	P06	V	C	1	1.83	(61.9)	(33.8)	4	e
					4	1.61	(31.2)	(19.4)		e
					5	1.10	(36.8)	(33.0)		e
C-C	"Whitehorse"	W03	VI	D	5	0.99	8.6	8.7	6	
					6	1.05	10.5	9.9		
					7	1.27	6.2	4.9		
					8	1.11	9.0	8.1		
					9	0.86	11.9	13.9		
		W14	V	D	5	1.19	6.2	5.2	6	
					6	0.86	10.0	11.7		
					7	1.09	4.3	3.9		
					8	1.07	15.4	14.3		
					9	0.86	8.2	9.6		
C-D	"Northeast"	C03	VII	E	3	0.92	4.3	4.7	7	
All Areas (edited data)		Mean				0.96	6.9	7.3		
		σ_{n-1}				0.14	3.4	3.4		

Chimney Types

Code	Description
I	Unlined masonry chimney located primarily inside the exterior walls of the house
II	Tile-lined masonry chimney located primarily inside the exterior walls of the house
III	Unlined masonry chimney located primarily outside the exterior walls of the house
IV	Tile-lined masonry chimney located primarily outside the exterior walls of the house
V	Prefabricated metal chimney located primarily inside the exterior walls of the house
VI	Prefabricated metal chimney located primarily outside the exterior walls of the house
VII	Stainless steel liner (8" diameter) inside masonry chimney primarily located inside the exterior walls of the house.

(continued)

Table III-6
(continued)

Comments:

a. The combination of catalytic woodstove model "C-A" with catalytic combustor model "A" is no longer available to the consumer as of July 1, 1988. Woodstove model "C-A" is only available with combustor "B." For this reason, these emission rate values are deleted from the data base used to develop emission factors.

b. Home V11 had the highest overall mean fuel load (12.7 kg) and the lowest overall mean loading frequency (0.09 lb/hr) of all homes, with stove model C-A in the "Northeast" Study. This type of fuel loading practice may have contributed to the observed relatively low emission rates.

c. An inspection of the emission control system of the woodstove in this home conducted in August 1987 revealed: loose bypass damper gasket; weld gaps on the bypass damper door; bi-metallic coil tension set-point on the thermostat was improperly set; and the gasket around the catalyst had gaps. Using EPA Methods 28 and 5G, it was determined the catalyst in this stove had prematurely failed. However, it could not be determined if the catalytic combustor emission reduction performance failure was due to inherent material defects in the catalyst and/or due to the stove installation and/or woodstove manufacturing problems.

d. An inspection of the emission control system in this stove in August 1987 revealed that the catalytic combustor was not properly seated. This improper seating may have contributed to the seesaw emission rates values observed. The improper seating of the catalyst was probably due to improper installation procedures.

e. An inspection of the emission control system of this stove conducted after the collection of emission samples revealed the following:

   1. Approximately 22.9 cm (9 inches) of the glass fiber gasket that seals the catalyst bypass damper was missing on the bottom edge of the damper. The gasket is normally fitted into a groove located on the damper door. During fuel loading events, the bypass damper door is opened, exposing the gasket. It is hypothesized that the missing gasket may have been caused by fuel, e.g., logs, 2 by 4s, etc., contacting the gasket, since the missing gasket material was in the area most exposed to the type of potential physical abrasion. Since this observation is based on one stove, it is difficult to determine if the problem is a stove design and/or operator related issue.

   2. A portion of the missing bypass damper gasket had fallen into the hinge of the bypass door, which did not allow the bypass door to seal properly. A 0.6 cm ($^1/_4$ inch) gap between the bypass door and its jamb was formed when the missing gasket acted as a wedge. There was no detectable tactile indication of whether the bypass door was fully closed or partially open when operating the damper lever. The lack of tactile "feedback" to determine if the bypass damper door is fully closed appears to be a design problem.

(continued)

Table III–6
(continued)

3. Approximately one-third of the catalyst cells were plugged with ash. The "upstream" or combustion gas inlet side of the catalyst is the top horizontal side of the catalyst. This configuration can lead to a buildup of ash on the top surface of the catalyst versus the more common configuration where the "upstream" side of the catalyst is either the bottom horizontal or side face of the catalyst. Operator practices could also have contributed to the buildup of ash if an excessive amount of paper was used as fuel.

4. The gasket used on the removable ash pan located on the bottom of the woodstove indicated that the pan was not seating properly. This observation appeared to indicate that an underfire air condition may have occurred during the study. This type of combustion gas condition can cause elevated emissions through reduced combustion efficiency. Since this observation is based on only one stove, it is difficult to determine if the problem is a stove design and/or operator related issue.

5. It appears the study participant did not regularly inspect the woodstove's gaskets and mechanical components as recommended in the manufacturer's stove operating instruction booklet.

6. Operator inexperience: The woodstove was the first integral catalytic woodstove used by the participants in home P06. The participants in this home claimed that it took two weeks to learn how to operate the stove. Since there appears to be evidence that the operators of this stove, given adequate training regarding operating and maintenance procedures, may have avoided some, if not all, of the above identified problems, these emission rate values are deleted from the data base used in the development of catalytic woodstove emission factors.

1. Emission rates are the mean of the emission rates from co-located AWES units.

Table III-7

Installation, Burn and Particulate Emission Rate Characteristics
Noncatalytic Woodstoves (1988 NSPS Certified/Certifiable)

Stove Model	Study Area	Home Code	Chimney Type	Sample Period	Burn Rate dry kg/hr	Emissions g/hr	Emissions g/kg	Ref.	Comments
NC-A	"Northeast"	V12	II	6	0.67	5.2	7.7	2	
		V34	V	5	0.76	7.9	10.4	2	
				7	0.92	5.9	6.4		
		V35	V	7	0.90	3.6	4.0	2	
NC-B	"Northeast"	V03	II	5	1.28	18.3	14.3	2	
				6	1.38	2.0	1.4		
		V14	IV	6	1.07	26.3	26.6	2	a
				7	0.85	17.2	20.4		a
		N16	IV	4	0.97	10.0	10.3	2	
				6	1.10	4.3	3.9		
				7	0.87	10.3	11.9		
	"Northwest"	P04	V	1	1.29	6.9	5.3	4	
				2	0.99	10.0	10.1		
				3	0.90	10.9	12.1		
				4	0.65	6.7	10.3		
				5	0.70	6.9	9.9		
NC-C	"Northwest"	P01	II	1	0.87	(19.4)	(22.2)	4	b
				2	1.22	(17.4)	(14.3)		b
				3	1.07	(13.3)	(12.5)		b
				4	1.10	(24.1)	(21.8)		b
NC-D	"Whitehorse"	W04	VI	5	1.29	10.5	8.1	6	
				6	1.08	9.2	8.5		
				7	1.51	5.3	3.5		
				8	1.20	12.8	10.7		
				9	1.11	10.3	9.3		
		W09	V	5	1.01	(19.4)	(19.2)	6	c, d
				6	0.84	(18.3)	(21.8)		c
				7	0.91	(17.9)	(18.7)		c
				8	1.06	(17.9)	(16.8)		c
				9	0.85	(22.2)	(26.0)		c
All Areas (edited data)		Mean			1.02	9.5	9.8		
		σ_{n-1}			0.24	5.6	5.7		

(continued)

Table III-7
(continued)

Chimney Types

Code	Description
I	Unlined masonry chimney located primarily inside the exterior walls of the house
II	Tile-lined masonry chimney located primarily inside the exterior walls of the house
III	Unlined masonry chimney located primarily outside the exterior walls of the house
IV	Tile-lined masonry chimney located primarily outside the exterior walls of the house
V	Prefabricated metal chimney located primarily inside the exterior walls of the house
VI	Prefabricated metal chimney located primarily outside the exterior walls of the house

Comments:

a. According to Reference 2, there are no conclusive factors to explain the elevated emission rates observed for stove model "NC-B" in home V14.

b. The flue pipe of this stove entered a tile-lined masonry chimney that measured 17.8 cm by 27.9 cm by 3.7 meters high (7 inches by 11 inches by 12 feet high). Since the manufacturer of this stove recommended using a 15.24 cm (6 inch) diameter chimney, the attached chimney system may have been "oversized" for this woodstove model. An inspection of the stove between the first and second sampling periods revealed no obvious problems with the stove's emission control system. While it is possible operator practices could have contributed to the elevated emission rate performance, it is hypothesized that the oversized chimney system is a significant contributing factor to this stove's emission performance. For this reason, these emission values are deleted from the data base used to develop emission factors for noncatalytic woodstoves (1988 NSPS-certified/certifiable).

c. It is hypothesized that the configuration of the chimney system used in home W09 may have been a contributing factor to the observed emission rates. The relatively short length, 3.4 m (11.2 feet), of the chimney coupled with the mismatching of a 15.24 cm (6 inch) diameter flue pipe with 20 cm (8 inch) packed pipe may have resulted in relatively poor draft conditions and thereby influencing the combustion efficiency of the stove. The manufacturer recommends a uniform run of 15 cm (6 inch) diameter pipe. An inspection of the emission control system of this stove revealed no significant problems. For the above reasons, these emission rate values are deleted from the data base used to develop emission factors for noncatalytic woodstoves (1988 NSPS-certified/certifiable).

d. Ambient oxygen (O_2) value associated with emission sample greater than 20.9 ± 2.0 percent absolute at final calibration. Therefore, calculated emissions (g/hr, g/kg) have a potentially higher degree of associated uncertainty. Because of the higher uncertainty associated with this emission sample, it is deleted from the data base for calculating emission factors for noncatalytic woodstoves (1988 NSPS-certified/certifiable).

Table III-8

Mean Particulate Emission and Burn Rates by Woodstove Installation
Catalytic Woodstoves
(1988 NSPS Certified/Certifiable)

Study Area	Model	Home	Mean Emission Rates		Mean Burn Rate	Emission Samples
			g/hr (σ_{n-1})	g/kg (σ_{n-1})	dry kg/hr (σ_{n-1})	(N)
"Northeast"	C-A	C01	4.9 (0.28)	5.7 (0.56)	0.86 (0.03)	2
	C-D	C03	4.3 (0)	4.7 (0)	0.92 (0)	1
Avg (unweighted)			4.6 (0.42)	5.2 (0.70)	0.89 (0.04)	
Range			4.3 - 4.9	4.7 - 5.7	0.86 - 0.92	3
"Northwest"	C-A	P02	4.0 (0.77)	4.8 (1.45)	0.88 (0.14)	5
Avg (unweighted)			4.0 (0.77)	4.8 (1.45)	0.88 (0.14)	
Range			—	—	—	5
"Whitehorse"	C-B	W03	9.2 (2.1)	9.1 (3.2)	1.06 (0.15)	5
	C-B	W14	8.8 (4.3)	8.9 (4.4)	1.01 (0.15)	5
Avg (unweighted)			9.0 (0.28)	9.0 (0.14)	1.03 (0.03)	
Range			8.8 - 9.2	8.9 - 9.1	1.01 - 1.06	10
ALL AREAS						
Avg (unweighted)			6.2 (2.5)	6.6 (2.2)	0.95 (0.09)	
Range			4.0 - 9.2	4.7 - 9.1	0.86 - 1.06	18

Table III-9

Mean Particulate Emission and Burn Rates by Woodstove Model
Catalytic Woodstoves
(1988 NSPS Certified/Certifiable)

Stove Model	Study Area(s)	Homes(s)	Mean Emission Rates		Mean Burn Rate	Emission Samples
			g/hr (σ_{n-1})	g/kg (σ_{n-1})	dry kg/hr (σ_{n-1})	(N)
C-A	NE,NW	C01, P02	4.3 (0.77)	5.1 (1.3)	0.87 (0.11)	7
C-B	WH	W03, W14	9.0 (3.2)	9.0 (3.6)	1.03 (0.03)	10
C-D	NE	C03	4.3 (0)	4.7 (0)	0.92 (0)	1
Average (unweighted)			5.9 (2.7)	6.3 (2.4)	0.94 (0.08)	
Range			4.3 - 9.0	4.7 - 9.0	0.87 - 1.03	18

Table III-10

Mean Particulate Emission and Burn Rates by Woodstove Installation
Noncatalytic Woodstoves
(1988 NSPS Certified/Certifiable)

Study Area	Model	Home	Mean Emission Rates		Mean Burn Rate	Emission Samples
			g/hr (σ_{n-1})	g/kg (σ_{n-1})	dry kg/hr (σ_{n-1})	(N)
"Northeast"	NC-A	V12	5.2 (0)	7.7 (0)	0.67 (0)	1
	NC-A	V34	6.9 (1.0)	8.4 (2.0)	0.84 (0.08)	2
	NC-A	V35	3.6 (0)	4.0 (0)	0.90 (0)	1
	NC-B	V03	10.2 (8.2)	7.9 (6.5)	1.33 (0.05)	2
	NC-B	V14	21.8 (4.6)	22.5 (2.1)	0.96 (0.11)	2
	NC-B	N16	8.2 (2.8)	8.7 (3.5)	0.98 (0.09)	3
Avg (unweighted)			10.1 (7.5)	10.2 (7.0)	0.94 (0.22)	
Range			3.6-21.8	4.0-22.5	0.67 - 1.33	11
"Northwest"	NC-B	P04	8.3 (2.0)	9.5 (2.5)	0.91 (0.26)	5
Avg (unweighted)			8.3 (2.0)	9.5 (2.5)	0.91 (0.26)	
Range			—	—	—	5
"Whitehorse"	NC-D	W04	9.6 (2.7)	8.0 (2.7)	1.06 (0.14)	5
Avg (unweighted)			9.6 (2.7)	8.0 (2.7)	1.06 (0.14)	
Range			—	—	—	5
ALL AREAS						
Avg (unweighted)			9.2 (5.5)	9.6 (5.5)	0.96 (0.19)	
Range			3.6-21.8	4.0-22.5	0.67 - 1.33	21

Table III-11

Mean Particulate Emission and Burn Rates by Woodstove Model
Noncatalytic Woodstoves
(1988 NSPS Certified/Certifiable)

Stove Model	Study Area(s)	Homes(s)	Mean Emission Rates		Mean Burn Rate	Emission Samples
			g/hr (σ_{n-1})	g/kg (σ_{n-1})	dry kg/hr (σ_{n-1})	(N)
NC-A	NE	V12, V34, V35	5.6 (1.8)	7.1 (2.7)	0.81 (0.12)	4
NC-B	NE,NW	V03, V14, P04	10.8 (6.8)	11.3 (6.9)	1.00 (0.23)	12
NC-D	WH	W04	9.6 (2.7)	8.0 (2.7)	1.23 (0.17)	5
Average (unweighted)			8.7 (2.7)	8.8 (2.2)	1.01 (0.21)	
Range			5.6-10.8	7.1-11.3	0.81 - 1.23	21

IV. RESULTS & DISCUSSION

A. TRADITIONAL TECHNOLOGY WOODSTOVE EMISSION FACTORS

Table IV-1 lists the number of emission samples used in the development of emission factors, woodstove installations, and woodstove models per study area. Confidence limits based on the data in Tables III-2, III-3, III-4, and IV-1 are shown in Table IV-2. While there are relatively small differences between the calculated emission factors, the confidence interval is influenced by the data base size (N) and standard deviation (σ). Since (1) the data in Table III-3 showed significant emission rate variability between homes with the identical woodstove models and (2) there are potentially thousands of different woodstove model/chimney system installation combinations, it is recommended that the data in Table III-3 be used as the basis for calculating traditional technology woodstove emission factors and related statistics. Presented in Table IV-3 are the recommended emission factors (g/hr, g/kg) and related statistics based on data in Table III-3.

The average area-specific gram-per-kilogram emission factors and burn rates in Table III-3 show a correlation coefficient (r) of -0.96 (Table IV-4). This inverse relationship supports laboratory data which indicates that emission rates decrease with increasing burn rate for most traditional technology woodstoves. Higher burn rates will generally result in lower emissions due to increased firebox temperatures and more complete combustion of fuel and its combustion gases. While this relationship is based on a limited data base, it may be of assistance to users in calculating a gram-per-kilogram emission factor based on the "average" burn rate conditions in a specific geographic area. The range of burn rates upon which this relationship was developed is 0.80 to 2.25 dry kg/hr. Based on the data in Table III-3, there appears to be no statistically significant correlation between the area-specific gram per hour emission factors and burn rates ($r = 0.05$). There is no significant correlation between woodstove model-specific emission and burn rates ($r = 0.40$, $r = -0.38$, respectively) based on the data in Table III-4.

As noted in the comments in Table III-2, there may have been factors, e.g. fueling practices and chimney system configuration, that may have contributed to relatively low or elevated emission rates. However, the range of average emission rates (g/hr, g/kg) did not vary significantly between all three study areas (Table III-3). In each area there were traditional technology woodstoves that produced emission rates under 10 g/hr. Therefore, it did not appear to be justifiable to remove low emission rates from the data base just because there were below the expected emission rates for traditional technology woodstoves.

An unresolved question still remains as to the "true" population gram-per-hour (or gram-per-kilogram) mean emission rates in each of the study areas. The variability of emission rates between homes with the same woodstove model is significant. While the amount of data showing inter-home emission rate variability with

Table IV-1

Data Base Sample Sizes
Traditional Technology Woodstoves

Study Area	Emission Samples	Woodstove Installations	Stove Models
"Northeast"	14	6	6
"Northwest"	12	4	4
"Whitehorse"	53	16	9
All Areas	79	26	17 *

* One of the stove models (T-B) was installed in all three study areas.

Table IV-2

Confidence Intervals
Traditional Technology Woodstoves

Emission Factor	Confidence Limit	Data Base Used for Calculations		
		"Emission Samples"[1]	"Woodstove Installations"[2]	"Stove Model"[3]
g/hr	95%	21.0 ± 1.9	21.3 ± 2.8	20.4 ± 3.2
	99%	21.0 ± 2.5	21.3 ± 3.7	20.4 ± 4.4
g/kg	95%	15.4 ± 1.3	15.2 ± 1.8	14.6 ± 2.2
	99%	15.4 ± 1.7	15.2 ± 2.4	14.6 ± 2.9

1. Calculations based on individual emission sample emission rates (Table III-2). $N = 79$, $\sigma_{g/hr} = 8.6$, $\sigma_{g/kg} = 5.9$.

2. Calculations based on average "woodstove installation" emission rates (Table III-3). $N = 26$, $\sigma_{g/hr} = 7.4$, $\sigma_{g/kg} = 4.7$.

3. Calculations based on average "woodstove model" specific emission rates (Table III-4). $N = 17$, $\sigma_{g/hr} = 7.0$, $\sigma_{g/kg} = 4.6$.

Table IV–3

Recommended Particulate Emission Factors
Traditional Technology Woodstoves

	g/hr	g/kg
Emission Rate	21.3	15.2
Standard Deviation	7.4	4.7
Range	8.1 – 33.0	5.5 – 23.9
95% Confidence Interval	21.3 ± 2.8	15.2 ± 1.8
99% Confidence Interval	21.3 ± 3.7	15.2 ± 2.4

Table IV–4

Relationship Between Area-Specific Average Gram per Kilogram Particulate Emissions and Burn Rates
Traditional Technology Woodstoves

Location	Average Emission Rate (g/kg)	Average Burn Rate (dry kg/hr)
"Northeast"	12.6	1.65
"Northwest"	17.2	1.19
"Whitehorse"	15.8	1.45

$r = -0.96$ $r^2 = 0.92$

Regression Equation: $y = -9.77\,x + 29.2$,

where

x = Area-specific average burn rate, dry kg/hr; and

y = Emission rate, g/kg.

the same woodstove model is limited (only 5 woodstove models), the data do indicate a high degree of uncertainty of determining average model-specific emission rates based on data bases which include only one or two homes. Since all the data bases in the "Northeast" and "Northwest" studies are small and based on data sets of one specific woodstove model in only one home, it is highly probable that the calculated area-specific mean emission rates in Table III-3 are not representative of the "true" population. It may be more of a coincidence than any real relationship that the absolute difference in mean emission rates between all three study areas is 2.0 g/hr.

There is some inferential evidence that the area-specific mean emission rates (g/hr, g/kg) for the "Northeast" and "Northwest" studies may be higher than indicated by the data in Table III-3. The average area-specific burn rate for the "Northeast" study (1.65 kg/hr) is based on fourteen (N = 14) emission samples listed in Table III-2. A limited analysis of the frequency distribution of traditional technology woodstove burn rates from homes V09, V14, and N16 during the 1985-86 heating season indicated a mean burn rate of 1.39 dry kg/hr (refer to Table IV-5). This analysis includes all the time the woodstoves were operational (including non-AWES sampling periods) as determined by electronic data logging equipment. Burn rates were determined on twenty-four-hour time periods (5AM-5AM) between December 20, 1985 and April 7, 1986 (N = 166). Since it appears that at least area-specific gram-per-kilogram emission rates are inversely proportional to burn rate (equation in Table IV-4), the "true Northeast" gram-per-kilogram emission rate may be approximately 15 to 16 g/kg rather than the calculated 12.6 g/kg (Table III-3).

The area-specific emission rates for the "Northwest" study are based on emission rates for woodstove models T-B, T-D, T-J, and T-K. There is some inferential evidence that for at least woodstove model T-K typical "Northwest" emission rates for this woodstove model may be higher than indicated in Table III-3. A study performed for the Oregon Department of Environmental Quality (ODEQ)[14] evaluating a catalytic add-on device determined mean before-catalyst emission rates of 29.2 g/hr and 28.5 g/kg for woodstove model T-K. These rates were based on four emission samples collected in two homes (two samples per home). Assuming approximately a 10 percent increase in before-catalyst emission rates (based on analysis of data in the "Whitehorse" study[6]) due to the "dampering" effect of the add-on devices, the corrected flue collar emission rates would be approximately 26 g/hr and 24 g/kg at a burn rate of 1.1 dry kg/hr.

Since the recommended emission rates are based on a relatively small data base, the user of the recommended emission factors should recognize the limitations of the data and apply the appropriate caveats, e.g., use confidence limits, when using the recommended emission rates on either an absolute or relative comparison basis.

Table IV-5

Burn Rate Frequency Distribution – "Northeast"

OMNI Environmental Services, Inc.

****

Daily (5 am to 5 am) Burn Rates Calculated as TC#1>100

Files:

V09.HRW:	01-21-86	(2100)	to	03-03-86	(1400).	Number of points: 38
V14.HRW:	01-24-86	(1500)	to	03-31-86	(1100).	Number of points: 43
N08.HRW:	01-17-86	(1500)	to	04-02-86	(1400).	Number of points: 38
N16.HRW:	12-20-85	(1600)	to	12-23-85	(0600).	Number of points: 2
N16.HRW:	01-29-86	(1800)	to	04-07-86	(0900).	Number of points: 45

Total # Data Points: 166

Burn Rate Interval (kg/hr)	# of Points	Frequency (%)	Cumulative Frequency (%)
> 0.000 - 0.100	0	0.0	0.0
> 0.100 - 0.200	0	0.0	0.0
> 0.200 - 0.300	0	0.0	0.0
> 0.300 - 0.400	2	1.3	1.3
> 0.400 - 0.500	2	1.3	2.6
> 0.500 - 0.600	5	3.2	5.8
> 0.600 - 0.700	3	1.9	7.7
> 0.700 - 0.800	4	2.6	10.3
> 0.800 - 0.900	8	5.2	15.5
> 0.900 - 1.000	7	4.5	20.0
> 1.000 - 1.100	15	9.7	29.7
> 1.100 - 1.200	14	9.0	38.7
> 1.200 - 1.300	11	7.1	45.8
> 1.300 - 1.400	14	9.0	54.8
> 1.400 - 1.500	14	9.0	63.9
> 1.500 - 1.600	12	7.7	71.6
> 1.600 - 1.700	11	7.1	78.7
> 1.700 - 1.800	9	5.8	84.5
> 1.800 - 1.900	2	1.3	85.8
> 1.900 - 2.000	3	1.9	87.7
> 2.000 - 2.100	1	0.6	88.4
> 2.100 - 2.200	5	3.2	91.6
> 2.200 - 2.300	3	1.9	93.5
> 2.300 - 2.400	3	1.9	95.5
> 2.400 - 2.500	1	0.6	96.1
> 2.500 - 2.600	0	0.0	96.1
> 2.600 - 2.700	1	0.6	96.8
> 2.700 - 2.800	1	0.6	97.4
> 2.800 - 2.900	0	0.0	97.4
> 2.900 - 3.000	1	0.6	98.1
> 3.000 - 3.100	1	0.6	98.7
> 3.100 - 3.200	0	0.0	98.7
> 3.200 - 3.300	1	0.6	99.4
> 3.300 - 3.400	1	0.6	100.0
> 3.400 - 3.500	0	0.0	100.0
> 3.500 - 3.600	0	0.0	100.0
> 3.600 - 3.700	0	0.0	100.0
> 3.700 - 3.800	0	0.0	100.0
> 3.800 - 3.900	0	0.0	100.0
> 3.900 - 4.000	0	0.0	100.0
> 4.000 - 4.100	0	0.0	100.0
> 4.100 - 4.200	0	0.0	100.0
> 4.200 - 4.300	0	0.0	100.0
> 4.300 - 4.400	0	0.0	100.0
> 4.400 - 4.500	0	0.0	100.0
> 4.500 - 4.600	0	0.0	100.0
> 4.600 - 4.700	0	0.0	100.0
> 4.700 - 4.800	0	0.0	100.0
> 4.800 - 4.900	0	0.0	100.0
> 4.900 - 5.000	0	0.0	100.0
Days when stove was not in use	11	----	----

Mean Burn Rate : 1.397
Standard Deviation: 0.550

B. 1988 NSPS-CERTIFIED/CERTIFIABLE WOODSTOVE EMISSION FACTORS

As of July 21, 1988, there were 72 catalytic and 43 noncatalytic woodstove models that had been grandfathered or directly certified under the 1988 NSPS.[15] Only 4 woodstoves out of a total of 115 were directly certified. Therefore, the NSPS certified/certifiable woodstove models used as the basis for determining emission factors represent only 4 percent of the approved catalytic units and 7 percent of the approved noncatalytic units. In addition, none of the woodstoves evaluated in the field studies were directly certified under NSPS requirements. Tables IV-6 and IV-7 present the number of acceptable emission samples collected, woodstove installations, and stove models used per study for catalytic and noncatalytic technologies. Confidence intervals for calculated mean emission rates are shown in Tables IV-8 and IV-9 for catalytic and non-catalytic technologies, respectively.

Because of the limited data available, and the demonstrated degree of variability in emission rates between homes (installations) with the same stove model, recommended emission factors are based on the data in Tables III-8 (catalytic technology) and III-10 (noncatalytic technology). Tables IV-10 and IV-11 present the recommended emission factors and related statistics for 1988 certified/certifiable catalytic and noncatalytic woodstove technologies. A comparison of the recommended gram-per-hour emission factors for 1988 NSPS certified/certifiable catalytic and noncatalytic woodstoves with the 1988 (Phase 1) NSPS emission limits is shown in Table IV-12.

The differences between the 1988 NSPS (Phase I) emission limits and recommended emission factors can be attributed to differences between the standardized fueling protocol used for certified woodstoves (EPA Method 28)[1] and the variability associated with *in-situ* woodstove fueling, operating, installation, and maintenance conditions. An additional contributing factor could be that the woodstoves used as the basis for determining emission factors basically represent "first generation" emission control technologies, which were certified under the less stringent (as compared to EPA NSPS direct-certification provisions) Oregon rules. It is expected as emission control technology improves for NSPS-certified woodstoves that a more consistent pattern of relatively low emission rate performance will be demonstrated.

Due to the limited number of emission samples used to derive the recommended particulate emission factors, no adjustment factors based on burn rates are proposed. As in the case with the recommended emission factors for traditional technology woodstoves, the user should recognize the limitations of the data and apply the appropriate caveats, e.g., use confidence limits, when using the recommended emission factors on either an absolute or relative comparison basis.

Table IV-6

Data Base Sample Sizes
Catalytic Woodstoves
(1988 NSPS Certified/Certifiable)

Study Area	Emission Samples	Woodstove Installations	Stove Models
"Northeast"	3	2	2
"Northwest"	5	1	1
"Whitehorse"	10	2	1
All Areas	18	5	3 *

* One of the stove models (C-A) was installed in two study areas.

Table IV-7

Data Base Sample Sizes
Noncatalytic Woodstoves
(1988 NSPS Certified/Certifiable)

Study Area	Emission Samples	Woodstove Installations	Stove Models
"Northeast"	11	6	2
"Northwest"	5	1	1
"Whitehorse"	5	1	1
All Areas	21	8	3 *

* One of the stove models (NC-B) was installed in two study areas.

Table IV–8

Confidence Intervals
Catalytic Woodstoves
(1988 NSPS Certified/Certifiable)

Emission Factor	Confidence Limit	Data Base Used for Calculations		
		"Emission Samples"[1]	"Woodstove Installations"[2]	"Stove Model"[3]
g/hr	95% 99%	6.9 ± 1.6 6.9 ± 2.1	6.2 ± 2.2 6.2 ± 2.8	5.9 ± 3.0 5.9 ± 3.7
g/kg	95% 99%	7.3 ± 1.6 7.3 ± 2.1	6.6 ± 1.9 6.6 ± 2.5	6.3 ± 2.7 6.3 ± 3.6

1. Calculations based on individual emission sample emission rates (Table III–6).
   $N = 18$, $\sigma_{g/hr} = 3.4$, $\sigma_{g/kg} = 3.4$.
2. Calculations based on average "woodstove installation" emission rates (Table III–8).
   $N = 5$, $\sigma_{g/hr} = 2.5$, $\sigma_{g/kg} = 2.2$.
3. Calculations based on average "woodstove model" specific emission rates (Table III–9).
   $N = 3$, $\sigma_{g/hr} = 2.7$, $\sigma_{g/kg} = 2.4$.

Table IV–9

Confidence Intervals
Noncatalytic Woodstoves
(1988 NSPS Certified/Certifiable)

Emission Factor	Confidence Limit	Data Base Used for Calculations		
		"Emission Samples"[1]	"Woodstove Installations"[2]	"Stove Model"[3]
g/hr	95% 99%	9.5 ± 2.4 9.5 ± 3.1	9.2 ± 3.8 9.2 ± 5.0	8.7 ± 3.1 8.7 ± 4.0
g/kg	95% 99%	9.8 ± 2.5 9.8 ± 3.2	9.6 ± 3.8 9.6 ± 5.0	8.8 ± 2.5 8.8 ± 3.3

1. Calculations based on individual emission sample emission rates (Table III–7).
   $N = 21$, $\sigma_{g/hr} = 5.6$, $\sigma_{g/kg} = 5.7$.
2. Calculations based on average "woodstove installation" emission rates (Table III–10).
   $N = 8$, $\sigma_{g/hr} = 5.5$, $\sigma_{g/kg} = 5.5$.
3. Calculations based on average "woodstove model" specific emission rates (Table III–11).
   $N = 3$, $\sigma_{g/hr} = 2.7$, $\sigma_{g/kg} = 2.2$.

Table IV-10

Recommended Particulate Emission Factors
Catalytic Woodstoves
(1988 NSPS Certified/Certifiable)

	g/hr	g/kg
Emission Rate	6.2	6.6
Standard Deviation	2.5	2.2
Range	4.0 - 9.2	4.7 - 9.1
95% Confidence Interval	6.2 ± 2.2	6.6 ± 1.9
99% Confidence Interval	6.2 ± 2.8	6.6 ± 2.5

Table IV-11

Recommended Particulate Emission Factors
Noncatalytic Woodstoves
(1988 NSPS Certified/Certifiable)

	g/hr	g/kg
Emission Rate	9.2	9.6
Standard Deviation	5.5	5.5
Range	3.6 - 21.8	4.0 - 22.5
95% Confidence Interval	9.2 ± 3.8	9.6 ± 3.8
99% Confidence Interval	9.2 ± 5.0	9.6 ± 5.0

Table IV-12
Comparison of 1988 (Phase I) NSPS Emission Limits
with Recommended 1988 NSPS Emission Factors

Technology	Phase I Emission Limits (g/hr)	Recommended 1988 NSPS Emission Factors (g/hr)
Catalytic	5.5	6.2
Noncatalytic	8.5	9.2

V. REFERENCES

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